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MANNED SPACE VEHICLE BATTERY SAFETY HANDBOOK

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PREFACE

This handbook has been prepared for use by designers of battery-operated equipment. The purpose is to provide such people with information on design provisions necessary to incorporate in and around the battery to result in a design which is safe. Safe, in this connection, means safe for ground personnel and crew to handle and use; safe to use in the enclosed environment of a manned space vehicle and safe to be mounted in adjacent, unpressurized spaces.

Each new battery-operated equipment proposed for flight is evaluated by JSC engineers for battery safety. If the design is judged unsafe, changes must be made to make it safe. Using this handbook can result in savings of time and money by optimizing safe design beforehand.

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1.0 INTRODUCTION

There have been many requests for a document which describes all hazards associated with use of batteries in and on manned space vehicles and alternative acceptable controls for these hazards. This information is desired for designers of battery-operated equipment so that their original designs can accommodate these hazard controls. In the past a nearly complete (or completed) design has been evaluated, more or less after the fact, and changes in the battery area have often been required. This document describes the things that a design engineer should consider in order to verify control of hazards to personnel and equipment. Hazards to ground personnel who must handle battery-operated equipment are considered as well as hazards to space crew and vehicles.

To preclude unexpected schedule and cost impacts, it is suggested that contact be made with battery engineers in the Electrochemical Power Section of the Power Branch of Johnson Space Center, as early as possible in the design process.

2.0 PURPOSE

It is the purpose of this document to cover battery safety, not performance. However, many of the hazard controls enhance performance reliability since they are designed to prevent hazards which are the result of failures. For example, prevention of electrolyte leakage and grounding in a battery case which may cause a battery explosion also prevents aborted battery operation.

The contents of this document are not considered to cover every conceivable exigency. They do contain nearly everything known by the authors which is applicable in this technical area (battery safety), however.

There is no attempt herein to provide knowledge of the theory and electrochemistry of batteries, except as necessary to elucidate a hazard or its control. A bibliography of readable texts, papers, proceedings, etc. is given at the end of this document for those who want to learn more about batteries generally.

Although this document is prepared with portable batteries and portable battery operated equipment in mind, many of the hazards and controls apply equally to larger, main power types of batteries.

3.0 CONTENT

For user convenience, the following describes the sequence of subjects covered herein.

First, precautions applicable to nearly all batteries are described. Hazards are described, followed by applicable controls with optional controls where known and feasible.

Next, individual cell types having unique hazards are described, followed by appropriate controls or options.

Next, material is presented as to permissible failure levels and general safety practices applicable to batteries.

4.0 USABLE BATTERY TYPES

Inquiries are frequently received as to a listing of batteries "approved" for use onboard the Shuttle. There is no such list. Any battery which can be made safe to fly in the manned spacecraft environment can be used. There are some kinds of batteries it is not practical to make safe. For example, a battery with large amounts of free electrolyte (e.g., automobile battery) presents huge problems in a zero g environment to prevent electrolyte escape. As another example, lithium-sulfur dioxide cells have built-in overpressure reliefs which release SO_2 and other electrolyte components whenever internal cell pressure is high enough. This is unacceptable in the closed environment of the Orbiter cabin.

The following is a listing of types of cells which have already been flown in or on the Orbiter:

- Silver oxide-zinc primary (one-shot) and secondary (rechargeable)
- Nickel-cadmium secondary
- Nickel-hydrogen secondary
- Alkaline-manganese primary
- LeClanche (carbon-zinc) primary
- Zinc-air primary
- Lead-acid secondary cells having immobilized electrolyte
- Mercuric oxide-zinc primary
- Lithium primary cells having the following cathodic (positive) active materials:
    - Thionyl chloride
    - Thionyl chloride with bromine chloride complexing additive (Li-BCX)
    - Sulfur dioxide (external to habitable spaces)
    - Monocarbon fluoride
    - Manganese dioxide
    - Iodine
    - Silver chromate

It must be noted that lithium-based cells are subject to extremely close review and are required to have seemingly excessive hazard controls incorporated in and on them. They can yield extremely high energies per unit weight and volume relative to other cell types. They have uniquely hazardous failure modes. For many types of lithium batteries, there are little comprehensive data which characterize either performance or response to abusive or off-nominal exposure. The chemicals contained in them are usually either highly flammable (e.g., lithium), corrosive and/or toxic (sulfur dioxide, hydrogen chloride, cyanide derivatives, etc.). In their various failure modes, they are subject to leakage, venting (spewed leaks) or violent explosions accompanied by scattered shrapnel and toxic materials. Hence, no effort is spared in providing utmost assurance that every known or suspected failure mode is prevented by effective hazard controls. Use of other types of cells is strongly encouraged wherever feasible. Weight and volume differences alone are not necessarily sufficient justification for use of lithium-based cells.

Use of batteries of any chemistry, including those listed above, may require extensive testing, evaluation and use of source controls. Certification prior to flight is always required.

5.0 GENERAL HAZARD SOURCES AND CONTROLS

5.1 SHORT CIRCUITS

5.1.1 Sources

Shorts can occur in the loads served by the battery, through conductive electrolyte leaks between cells within a battery or by careless contact with cell and battery terminals. Internal shorts in cells of batteries which have been prepared for flight by effective procedures are rare.

5.1.2 Hazards

a. A sustained short can result in extremely high temperature increases. Table I shows effects of shorting relatively benign alkaline-manganese cells and batteries through about 30 milliohms. Peak currents are reached in less than one second.

TABLE I
ALKALINE-MANGANESE SHORT CIRCUIT DATA

Cell or Battery Size	Peak Current (Amps)	Temperature Rise (°F)	Time to Peak Temperature (Minutes)
AA	9 to 11	33 to 95	2.5 to 7.2
D	8 to 12	64 to 83	31.5 to 48.3
9 volt (Rectangular)	8 to 10	102 to 170	5.5 to 8.7

b. High temperatures can result in surfaces which burn crewmen (113°F is the specification limit for touchable surfaces), meltdown of protective plastic structure surrounding the battery, release of noxious or explosive substances (hydrogen) or initiation of a fire.

c. In addition to heating, a short circuit through an electrolyte leak can decompose water in the electrolyte to hydrogen and oxygen, then provide the miniscule ignition energy (1-2 microjoules) to explode the hydrogen-oxygen mixture when the short circuit current terminates with a small arc at last contact. This type of failure is considered to have caused the LM descent battery explosion during the cis-lunar leg of the aborted Apollo 13 mission. Some obvious hazard controls had been omitted to save weight because such an event was considered unlikely. Apollo 14 and later LM batteries incorporated the controls.

5.1.3 Controls

a. Batteries must have circuit interrupters which are physically and electrically close to the battery and are rated well below the battery's short circuit current capability. Interrupters may be fuses, circuit breakers, thermal switches or any other effective device. The interrupter should be in the ground leg of batteries with metal cases so that battery grounds inside the battery case (usually grounded to structure) may be sensed and interrupted.

b. All inner surfaces of metal battery cases must be coated with an insulating paint known to be resistant to the battery electrolyte. This aids in preventing battery grounds to the case through electrolyte leakage.

c. Cell terminals must be protected from contact with other conductive surfaces by potting or by a non-conductive barrier (e.g., plastic sheet).

d. The parts of battery terminals extending inside the battery case must be insulated from unintentional contact with other conductors and bridging by electrolyte leaks. Potting may be used.

e. Battery terminals which pass through metal battery cases must be insulated from the case by an insulating collar or other effective means.

f. The parts of battery terminals on the outside of the battery case must be positively protected from accidental bridging. This may be accomplished by using a female connector, recessing stud-type terminals, installation of effective insulating barriers, etc.

g. Wire lengths inside the battery case must be insulated, restrained from contact with cell terminals and physically constrained from movement due to vibration or bumping.

5.2 ELECTROLYTE LEAKAGE

5.2.1 Sources

a. Excessive free electrolyte in vented cells.

b. Inadequate design of electrolyte trapping or baffling provisions under covers of vented cells.

c. Leakage through cracked cell containers.

d. Faulty seals on sealed cells.

e. Leakage of electrolyte forced through seals by cell overheating or overdischarge.

f. Other.

5.2.2 Hazards

a. Provides conductive ground paths between cells and to metal battery cases (see Short Circuits).

b. Electrolyte is corrosive to materials and personnel.

c. Electrolyte may be toxic to personnel as either a fluid or its vapors.

d. Aqueous electrolyte grounds may decompose to hydrogen and oxygen, providing an explosive gas mixture.

5.2.3 Controls

a. Excessive free electrolyte in vented cells should be corrected by cell tests in which the quantity of free electrolyte is reduced until cell capacity begins to be reduced. These tests must be conducted on cells whose age and cycle-life exposure (if any) is nearly identical to that proposed for flight cells. This sort of test applies mainly to silver oxide-zinc rectangular cells. The cell manufacturer generally specifies a slight excess of electrolyte be used because his cells are generally recharged several times by most customers. With increasing cycles of use, the excess free electrolyte is generally depleted by both water electrolysis and absorption in gradually expanding zinc negatives. Cells used in space are generally used on their first to fifth cycle and do not require excess free electrolyte. If subsequently used on the ground, electrolyte may be added, if desired.

b. Cell covers can be designed to have a cylindrical "stand-pipe" extend downward from the underside of the cell cover toward the cell plates, from the cell vent opening in the cover as shown in figure 1. Then when the cell is inverted in a gravity environment, the electrolyte level collecting on the inside of the cell cover is optimized not to rise above the opening of the "stand-pipe". This represents the worst case. All other cell positions, including zero g, are better.

c. Cells having free electrolyte must be fitted with relief valves in their vent ports, not just an opening and/or absorbent material. Relief valve opening pressures have ranged from 3 to 35 psid and are a function of the ability of the cell case to withstand internal pressure without cracking. Some steel-case rectangular NiCd cells are considered "sealed" because they use relief valves set to open at 100 to 200 psid. These are not the hermetically sealed, space-type NiCd cells which may also be used.

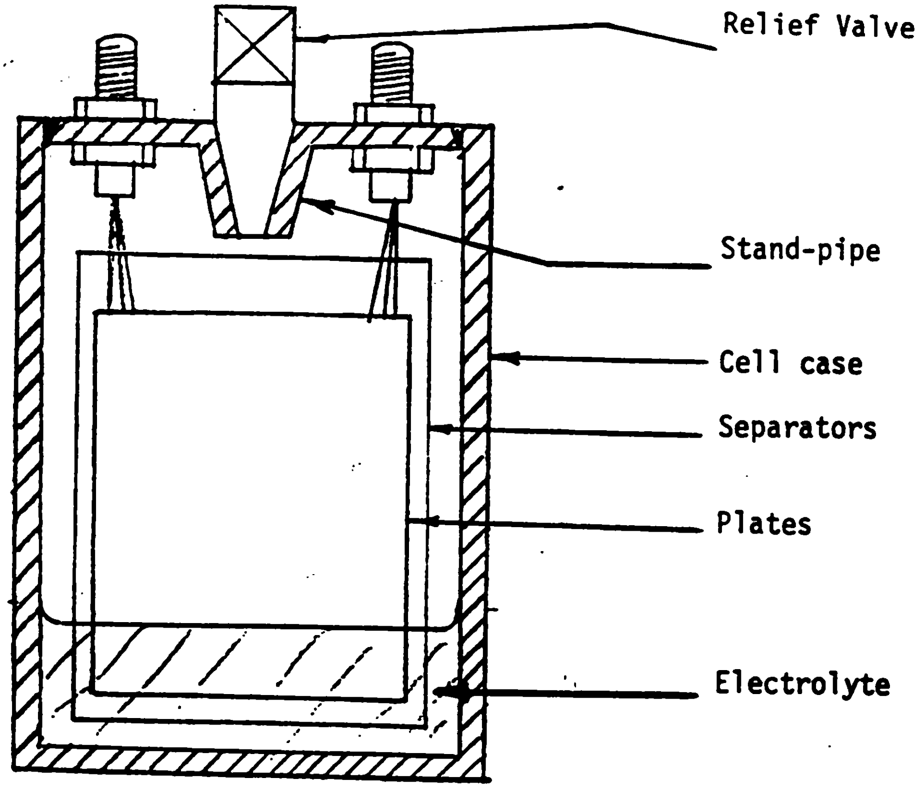
d. If inputs are feasible at the cell design level, microporous teflon plugs or sheet may be installed on the vent opening on the underside of the cell cover. Such material, if not covered over with electrolyte, will permit gas to escape but will prevent electrolyte escape due to its small pores and non-wetting property.

e. If it is not feasible to use the above controls, absorbent material (e.g., Furf or cotton wadding) has been used to fill the void spaces in a battery container or is placed directly over the cell vents. This is a less satisfactory control since electrolyte may be trapped against conductive parts by the absorbent material which may also be flammable.

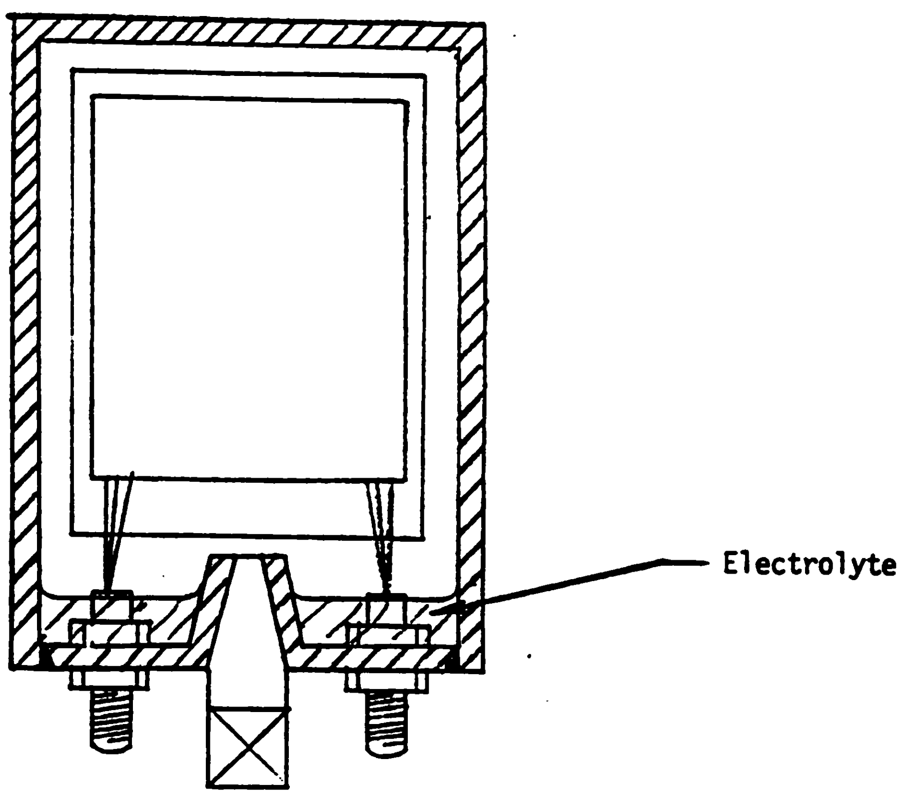
f. Internal surfaces of metal battery cases must be coated with an electrolyte resistant paint. (see 5.1.3b).

g. Require prelaunch stowage of batteries in the space vehicle to be oriented "upright" relative to gravity so that any free electrolyte is forced by earth gravity and launch acceleration into the cell plates and separators and away from cell seals or vents. This decreases the chance of in-flight leakage.

h. If inputs are possible at the initial design level of vented cells having free electrolyte, require as much extension of separator material beyond the cell electrodes as possible. This provides additional volume for capillary capture of the electrolyte, which then may require accelerative forces larger than 1g for dislodgement. In-flight maneuvers nearly always provide significantly less g's of force.



Cell Upright



Cell Inverted

Figure 1 - Spill Proof Cell Design

i. Prevent cell overheating due to internally generated heating on load by adequate heat removal provisions such as heat sinks or active cooling loops. As a rule of thumb, maximum allowable battery temperatures should not exceed 120°F. Higher temperatures require evaluation on an individual basis. If loss of battery power is tolerable, a heat-activated current interrupter should be used.

j. Prevent heating of batteries from externally imposed heat by insulating, shading, or installing away from heat sources, etc.

k. Prevent short circuits from any source. (See 5.1.3).

l. Cracked cell cases or seals may result from excessive internal pressure, failure to structurally support plastic cell cases which may be stressed by expansion as the battery is discharged, by wetting plastic cases with solvents which weaken them or cause crazing, etc. Vented cell cases should be tested by application of internal pressures equal to 1.5 times their relief valve maximum vent pressure. Cell cases should also be tested to determine their burst pressure. Adequate cell case support results from careful design. Contact with unevaluated solvents or known damaging solvents (e.g., benzene on ABS) is a quality control problem. Cracked seals on sealed cells which have no manufacturing defects may result from differential thermal expansion, internal overpressure resulting from excessive temperatures or overcharging. Thermal design or charging controls are required.

5.3 BATTERY GASES

5.3.1 Source

The primary gas evolved by cells which causes safety concerns is hydrogen. Any battery containing vented cells and using an aqueous electrolyte will generate hydrogen even under no-load status. Depending on prior handling, temperature and relief valve settings, hydrogen will be vented from the cells. See information on silver-zinc battery in Appendix A. (Lithium cells are covered later and may evolve toxic gases.)

5.3.2 Hazards

Hydrogen gas, mixed with air or oxygen is flammable or explosive over a wide range of concentrations; e.g., 3.8 percent to 94 percent in air. Accumulation of hydrogen in enclosed spaces containing oxygen must obviously be prevented. Aqueous electrolyte cells subjected to charging will generate oxygen as the charge nears completion, providing oxygen where none may have existed previously (due to nitrogen purging, for example). Wherever a flammable/explosive mixture of hydrogen and oxygen exist, an ignition source is <u>presumed</u> to exist although one may not be obviously identifiable. This is because energy required for ignition is on the order of 1 or 2 microjoules (1×10^{-6} watt-seconds).

5.3.3 Controls

a. The traditional means of avoiding hydrogen accumulation is to provide continuous air ventilation at a rate sufficient to continuously dilute evolved hydrogen below the 3.8 percent flammability level. For example, a lead-acid or silver oxide-zinc battery on overcharge is considered to evolve hydrogen at the rate expressed by the below expression:

$$Q = 0.016\ NI$$

Where
Q = cu. ft. H_2/hr. at 1 atm. and 77°F
N = no. of cells in battery
I = charging current in amperes

Thus, a battery of 20 cells on charge at 3 amps evolves:

$$Q = .016 \times 20 \times 3 = 0.96 \text{ cfh } H_2$$

To dilute the hydrogen to about 2 percent concentration in the ventilating air, the air flow must be:

$$\frac{0.96}{.02} = 48 \text{ cfh}$$

The value Q may be corrected for temperature and pressure by multiplying it by the value $K = 2.45P\ (T+460) \times 10^{-6}$ where, P equal actual pressure in mm Hg and, T equal actual temperature in °F. In practice, it is rarely feasible to ventilate hydrogen in Orbiter battery applications. Hence, one or more of the below controls must be exercised, whether or not charging is performed on board.

b. In applications used in habitable spaces of a vehicle, avoid the need for charging if any reasonable option exists.

c. Do not seal battery cases, but rather provide low pressure (3 to 15 psid) relief valves on the case. It is preferrable not to seal any secondary container in which the battery case is installed, unless a worst-case analysis shows flammable hydrogen-oxygen mixtures are not evolved into the container.

d. Minimize the volume of void spaces inside the battery case by design or by adding electrolyte-resistant, non-flammable filler such as potting. This limits the volume (and mass) of hydrogen which can accumulate prior to relief valve venting thus limiting the force of any hydrogen explosion.

e. Prohibit any component inside the battery case which may provide an ignition source, such as arcing between relay contacts. Stake or lock threaded fasteners or connections which may otherwise come loose and provide short circuits and arcing.

f. As close as possible to the time a battery is installed in the Orbiter, purge the battery case completely with dry nitrogen (or any other inert gas). Any secondary container in which the battery case is installed should also be purged, if at all feasible.

g. The provisions shown under 5.1 and 5.2 for preventing electrolysis of electrolyte leaks must be followed to prevent hydrogen and oxygen generation.

h. Minimize exposure of battery to high temperatures. (See Section 5.4)

5.4 HIGH TEMPERATURE EXPOSURE

For general purposes, high temperature is construed to mean temperature higher than 120°F. It is agreed that some batteries and some battery designs can safely and successfully operate at temperatures well above 120°F. Such instances are subject to review on the basis of individual circumstances surrounding each such battery application.

5.4.1 Sources

a. External heat: Direct and indirect solar radiation, heat from nearby hot surfaces, heat from adjacent hot components and heat from circuitry or hot fluid and gas loops.

b. Internal heat: Due to electrical losses within discharging or charging cells, heat is generated inside the cell. Figure 2 describes heat generation on discharge. Heat evolution on charge follows the same principle, except charge voltage is higher than open circuit voltage. During a short circuit, ΔV and I may both increase significantly. (See Figure 2)

5.4.2 Hazards

a. Excessive hydrogen gas generation: gas generation rates on open circuit double for each $10^{o}C$ temperature rise.

b. Electrolyte may be expelled along with vented gases at high gas generation rates or simply by thermal expansion of internal cell components, including the electrolyte itself.

c. Some cells, notably silver oxide-zinc, are subject to thermal runaway. At high temperatures, silver oxide decomposes, yielding oxygen. The released oxygen oxidizes zinc in the negative plates resulting in heat evolution and an increase in cell temperature which increases the silver oxide decomposition rate. This process cycle continues accelerating and can result in melting and charring of plastic cell cases and the extrusion of cell plate packs from cells.

5.4.3 Controls

a. Provide adequate short circuit protection (See 5.1).

b. Do not operate cells at loads above those set as maxima by battery manufacturers.

c. Perform a thermal analysis of the battery and its surroundings to verify probable battery temperatures under load and no-load conditions. This is particularly necessary for high energy, high power batteries installed in equipment stowed in the orbiter payload bay.

d. If the above battery thermal analysis shows that it will become cold enough to require heat inputs, electrical heaters must have redundant thermostatic overtemperature controls.

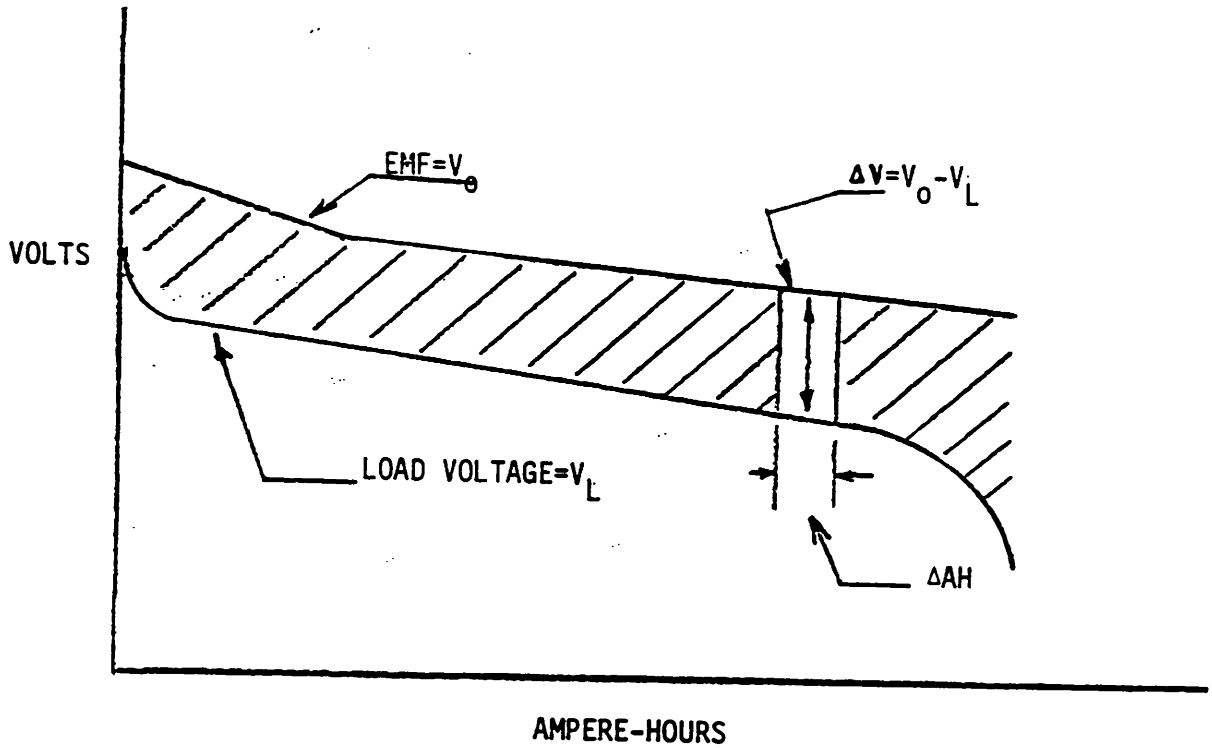
e. If the thermal analysis shows that any combination of external and internal heating may result in overtemperature, the following must be considered:

1. Provision of heat sinking, heat shunts or active cooling.

2. Provision of barriers from insolation or other convective, radiative or conductive heat sources.

3. Provision of thermally actuated circuit breakers to interrupt load current near hazardous temperatures.

Method for Calculating Heat Evolved during Cell Discharge



The EMF (V_o) of the cell is its open circuit voltage at each point during its discharge and is known before hand by previous measurements and by theory.

The load voltage (V_L) is measured throughout the discharge. The total heat evolved (Q) during a discharge is the integral of $\Delta V \times \Delta AH$ represented by the shaded area above. The instantaneous heat evolved, $\frac{\Delta Q}{\Delta t}$, is $\Delta V \times I$, where I is the current flowing at the place on the above curves where ΔV is obtained. For a constant resistance discharge, $\frac{\Delta Q}{\Delta t}$ equals $\Delta V \times \frac{V_L}{R}$, or, $\frac{\Delta Q}{\Delta t} = (V_o - V_L)\,\frac{V_L}{R}$.

FIGURE 2

4. Thermally optimized on-board location (move battery to cooler spot).

5.5 CIRCULATING CURRENTS

5.5.1 Sources

Circulating currents are unintended current flow, generally between cells or cell stacks connected in parallel. They can also occur between standby batteries and the prime power source they support, or through electrolyte leakage paths between cells. They result in parasitic discharging and/or unintended charging of cells in the circulating current loop. Circulating currents between parallel-connected cell stacks can result from lowered voltage in one or more stacks due to cell degradation, followed by current flow from adjacent electrically sound stacks due to the resulting difference in stack potentials.

5.5.2 Hazards

a. Hazards associated with currents circulating through electrolyte leakage paths are described under 5.2.2.

b. The hazard due to current flow between parallel stacks of cells, or between a standby battery and a prime power source, results from unintended charge and/or discharge. In aqueous electrolyte batteries, charging can result in water electrolysis with consequent hydrogen generation (See 5.3). Charging of lithium primary batteries is hazardous and is covered under 6.1.3.d. Unregulated discharging can result in overheating, the hazards of which are covered under 5.4.

5.5.3 Controls

a. Prevention of electrolyte leakage paths is covered under 5.2.

b. Circulating currents between parallel cells or cell stacks must be prevented by a blocking diode in each parallel leg. Small, conservatively current-rated Schottky barrier rectifiers have been used for this purpose to minimize voltage drop. As a practical matter, it is much better design to use larger capacity cells than many smaller cells in parallel. In the case of secondary batteries, severe charging current distribution problems can arise with parallel cell strings, requiring special charge current controls.

c. Current circulation from a prime power source to its back-up battery must also be prevented by a blocking diode. Depending on circuit power requirements, redundant controls such as a high resistance or a fuse in series with the battery may be installed. Another option is to put a relay in series with the battery which is held open by the prime power source. The special case of lithium standby batteries is covered under 6.1.3.

5.6 STRUCTURAL

5.6.1 Sources

Mechanical, chemical, and thermal stresses which reduce the integrity or functional capability of cell cases and battery cases.

5.6.2 Hazards

a. Breakage of mounting provisions, permitting unconstrained movement of battery.

b. Breakage of cell cases, permitting uncontrolled release of electrolyte and gases within battery case.

c. Breakage or other failure of battery case sealing provisions, also permitting uncontrolled release of electrolyte and gases to battery environment.

d. Fracture of internal current-carrying members resulting in arcing and explosion.

5.6.3 Controls

a. Verify vibration resistance of the battery assembly to the spectrum shown below by certification test or analysis:

Frequency	Range
20-80 Hz	+3dB/octave to. $067g^2$/Hz
80-350 Hz	$0.067g^2$/Hz
350-2,000Hz	-3dB/octave

Vibration should be for fifteen (15) minutes in each of the three axes of the assembly.

b. Verify shock resistance of the battery assembly to shock inputs of the below test by certification test or analysis:

Subject assembly to test of MIL-STD-810, Method 516.2, Procedure I. Apply a sawtooth shock pulse, 20g peak, 11 $\pm$1 millisecond rise and 1 $\pm$1 millisecond decay, once in each direction along each of the three orthogonal axes, for a total of six (6) shock pulses. This procedure is from the obsolete MIL-STD-810C version of the specification.

c. Battery cases are often made of lightweight materials such as aluminum alloy, magnesium alloy, plastics, etc. In such instances, a materials compatibility and stress analysis should be made to ensure maintenance of cell and battery case material strength and function after exposure to electrolyte, painted coatings, potting materials and their solvents, cleaning solutions used on them, cell case sealing materials and their solvents, or to any other material to which the battery may be exposed, within reasonable projection.

d. Battery cases should not be sealed (in the hermetical sense) but rather should have relief valves or other low pressure venting provisions installed. However, if a design is made which results in a gas-tight seal in spite of this constraint, the case must then meet the requirements of Paragraph 208.4 of NHB 1700.7A, Safety Policy and Requirements for Payloads Using the Space Transportation System (STS), regarding pressure vessel safety. If the battery case closure contains provision for low pressure venting and is otherwise sealed, it must meet the requirements of paragraph 208.7 of NHB 1700.7A regarding sealed containers. These requirements are exerpted in Appendix B.

e. Some cells swell during discharge. Silver oxide-zinc cells swell in the direction normal to the plane of their plates (electrodes). Zinc-air button cells swell axially; e.g., a Duracell 1200HP cell will lengthen axially about 0.015 inch during discharge. Battery development testing must include determinations of such dimensional changes. Battery case structural design must provide the strength to withstand or negate the stresses induced.

f. If it is known that significantly low or high temperatures will be experienced by the battery, whether from external or internal sources, account must be given to effects of differential thermal expansion and contraction between dissimilar materials; e.g., plastic cell cases and metal battery cases. In this example, plastic cell cases must not be "pinned" to a metal battery case by cement, hard potting or mechanical means. Resilient filler may also be required to absorb dimensional changes due to large temperature changes.

5.7 CHARGING

5.7.1 Sources

The charging referred to here is that which may be done on secondary batteries in or on the Orbiter while it is either in flight or awaiting launch on its launch pad. At present, this is nearly never done due to inaccessibility of batteries for charging or lack of necessity to charge. Most such charges will be freshening or trickle charges to "top-off" losses due to self discharge on stand. Therefore, the probability is great that cells will reach full charge quickly, then commence gas generation on overcharge as the charge is continued. Additionally, many cell failures occur preferrentially during charging, which is a battery stress condition.

5.7.2 Hazards

Gas generation during overcharge and cell failures (primarily internal cell short circuits) can evolve excessive amounts of heat and/or explosive gas mixtures or expel electrolyte fluid.

5.7.3 Controls

a. Use a battery design which does not require freshening or trickle charges. This is equivalent to saying do not use nickel-cadmium cells, since they have poor charged shelf-life. Nearly any other kind of cell has adequate shelf-life for shuttle missions. However, it may be necessary to use nickel-cadmium cells in applications requiring high power and low energy. Note that sealed nickel-cadmium cells on overcharge at or less than the manufacturer's recommended current and voltage are capable of recombining the generated oxygen within the cell. They therefore will not vent any gas under these conditions nor experience significant internal pressure rise.

b. Ground service or onboard chargers must be designed with all the performance precision and reliability of other space equipment. The voltage and current controls must follow output requirements determined during development testing or specified by the battery manufacturer to prevent excessive overcharge. Temperature adjustments of voltage and current may have to be included in the charger also.

c. Vented or pressure-relieved batteries requiring charging while in or on the shuttle on the launch pad must be mounted upright (tops of cells up, relative to the earth's gravity) so that any evolved gas is less likely to entrain electrolyte with it (See 5.2.3.g).

d. Charging Instructions must include a safety warning which bans the presence of any ignition source (smoking, welding, hammering, electrical relays or switches opening and closing, etc.) near batteries undergoing charge. If battery cells are truly hermetically sealed, as in the case of certain nickel-cadmium rectangular-cell satellite batteries, gas evolution presents no problem if charge voltage and current controls are adequate.

e. Charging instructions and instrumentation must provide for a ground check between the battery terminals (disconnected from external circuitry) and the battery case after charging. Minimum resistance should be greater than 1 megohm.

f. Where equipment batteries must be charged in flight, this fact must be addressed in the equipment safety analysis report.

6.0 SAFETY RELEVANT TO SPECIFIC BATTERY TYPES

6.1 LITHIUM BATTERIES

6.1.1 Definition

For the purpose of this document, a lithium cell is any cell using elemental lithium as its anode (negative electrode), whether its electrolyte and cathode consist of organic or inorganic chemicals, regardless of cell size, battery configuration, number of cells in a battery and regardless of location in or on the orbiter vehicle.

6.1.2 Hazard Sources

Lithium batteries have very high energy densities relative to other practical batteries. Table II gives a comparison of Li-BCX with other familiar battery systems.

Table II
Energy Density of D-Size Cells (Manufacturer's Data)

Cell Type	Watt-hrs / lb.	Watt-hrs / cu. in.
Carbon-zinc	17	1.2
Alkaline Managanese	37	3.8
Mercuric Oxide	41	5.7
Silver Oxide-Zinc*	80	7
Lithium - BCX	175	16.9

*Larger rectangular cell sizes.

Under unique and abusive conditions, lithium cells can be made to yield their contained energy suddenly and explosively. For example:

a. Any condition which results in the lithium anode reaching its melting point (367^{o}F). Heating conditions include application of external heat, externally applied short circuits, physical abuse (crushing, penetration by sharp object, etc.) which results in internal shorting, or failure to provide for removal of heat generated by internal losses while discharging at high rates.

b. Overdischarge. Any cell which is discharged until its voltage falls to zero volts and is then forced to continue discharging into negative voltage, whether by cells in series with it or by another power supply, is undergoing overdischarge (or forced discharge).

c. Charging long enough at a high rate, however low or high that may be for a particular lithium cell chemistry.

d. In addition to the above hazards, some lithium cells, e.g., lithium-sulfur dioxide, are designed with a burst disc in the cell case to relieve internal over-pressure under certain abusive use conditions. Clearly, a cell which may (by design) release toxic sulfur dioxide gas into the orbiter cabin is not acceptable.

6.1.3 Controls

a. Thermal Controls. Cell/battery temperatures must be controlled below the manufacturer's stated upper temperature limit; e.g., 160°F for Li-BCX. Testing should be done to verify safe performance at such limits. Account must be given to both external heat sources and heat generated by the cells due to internal losses on discharge (See 5.4.1). Methods of thermal control are given in 5.4.3.

b. Short Circuit Controls. Provide over-current protection devices such as fuses or circuit breakers, regardless of whether the cells have self-contained fuses. Protective devices should be rated above the highest likely load current, but well below the short circuit capability of the battery as established by test.

c. Overdischarge Protection. This does not apply to single cell batteries in applications where no external series power supply can be applied to the cell. Wherever more than one(1) cell is used in series, all cells must have one or more shunt diodes attached to them (depending on redundancy requirements) so that the diodes become conductive at the smallest possible negative voltage. Conservatively current-rated Schottky barrier rectifiers have been used on Orbiter equipment using Li-BCX batteries since they conduct at -0.25 to -0.3 volt, whereas silicon diodes require -0.5 to -0.6 volt for conduction. Strive for the least negative value. A low voltage cut-off circuit may be used wherever analysis supported by testing shows that the cut-off operates to remove load from the battery whenever any single cell in the battery nears zero voltage.

d. Charge Prevention. The basic control is to avoid paralleling batteries or strings of cells within a battery or paralleling batteries with other external power supplies, any of which may force a charging current through a stack of cells containing a weak or dead cell(s). However, if parallel strings of cells must be used, each string must contain its own blocking diode. Batteries which must be paralleled with external power sources must be equiped with charge current blocking devices. The special case of cells used to back up power supplies to memory circuits, CMOS, RAMS, timers, etc. has been covered by the JSC Power Branch memorandum EP5-84-M107 dated June 20, 1984, which is reproduced in its entirety in Appendix C.

6.1.4 Personnel Certification

As information, personnel at Johnson Space Center who are required to handle lithium batteries or cells are required to be certified under provisions of Chapter 9 (page I-9-9) of the JSC Safety Manual (JSC-1700D). This means that personnel must be trained in the safety hazards associated with lithium batteries and in appropriate controls against such hazards before they may routinely handle lithium batteries.

6.2 MERCURIC OXIDE-ZINC BATTERIES

6.2.1 Hazard Source

Each HgO-Zn cell contains at least 3.48 grams of mercury per ampere-hour of rated capacity. Thus, a Duracell RM-12 cell (AA penlight size) will contain at least 12.5 grams of mercury. Mercury vapor is toxic to the human central nervous system at continuous exposure of 0.01 milligram/cubic meter of air, or 8.3 parts per billion by weight. This equates to a toxic level of 0.69 milligrams in the 2450 cuft. void volume of the orbiter cabin. Additionally, metallic mercury readily amalgamates with many metals, including those used in Orbiter structure, causing embrittlement and failure. Under certain extra-nominal conditions (overheating, shorting, charging, etc.), cells may open, vent or burst, releasing mercury simultaneously.

6.2.2 Requirement

Mercuric oxide-zinc batteries are subject to Standard 116 of JSCM-8080, Manual of Manned Spacecraft Criteria and Standards, which is reproduced in its entirety in Appendix D. Thus, the mercuric oxide-zinc battery user must show why no mercury can escape, or show a decontamination plan for prompt recovery of all escaped mercury, or otherwise show why no decontamination plan is necessary. Application for waiver of all or part of Standard 116 can be made to the Space Shuttle Program Requirements Control Board (NASA Level II), which decides whether the waiver is permissable. This involves completing a JSC Form 281A, (Space Shuttle Program Level II Change Request). The form must be accompanied by justification data including analysis and results of abuse tests (short circuit, exposure to high temperatures (e.g., 350°F) overdischarge, shock, etc.) involving presumptive failure of cell seals. Finally, there is always the possibility that the waiver will not be granted, as in some recent instances.

6.2.3 Summary

From all of the foregoing, it should be clear that significant savings in time and expense may result from selection of a cell type having significantly less mercury content, such as alkaline-manganese or silver oxide-zinc. Note that almost all cells which use zinc negatives contain small amounts of mercury amalgamated with the zinc to reduce hydrogen gassing. This is generally not considered hazardous. Alkaline-manganese cells will be slightly heavier than mercuric oxide-zinc for the same energy content (See Table II) but are less expensive. Silver oxide-zinc cells are generally more expensive but may be lighter and smaller, depending on energy content. Neither requires special approval for mercury content.

7.0 PERMISSIBLE FAILURE LEVELS

As indicated earlier, battery safety and performance reliability are often inextricably involved with each other. Thus, some of the material below may seem like reliability requirements, however, their impact towards safe operation is clearly present.

7.1 PAYLOAD BATTERIES

Payload battery safety is given in Section 3.4.1.2 of JSC 11123, Space Transportation System Payload Safety Guidelines Handbook, nearly all of which is contained in this document. The permissible failure level (as applied to batteries) is that a battery must survive any single failure mode without inducing any of the hazards to crew and vehicle described on pages 2-1 to 2-3 of JSC-11123. These pages are reproduced herein as Appendix E.

7.2 CREW EQUIPMENT BATTERIES (NON-CRITICAL)

These equipments are covered by Document JSC-17038, Space Shuttle Program Flight Equipment Non-Critical Hardware Program Requirements Document.

Although there are virtually no requirements specific to batteries, the permissible failure level is classified as a "soft" failure. That is, any failure is permissible, so long as no credible failure can propagate outside the equipment or to a piece of critical equipment.

A listing of non-critical equipment is given in this document also and consists of things like calculators, cameras, multimeters, tape recorders, etc.

7.3 CRITICAL EQUIPMENT

Critical equipments are those whose functional failure can result in loss of the vehicle, harm to personnel or inability to achieve primary mission operational objectives. The permissible failure levels are described in terms of one and two successive failure modes. No single failure shall result in damage to equipment or require resort to contingency or emergency procedures. No subsequent second failure shall result in the potential for personnel injury, loss of the vehicle, ground facilities or Shuttle equipment.

7.4 SPACE STATION

The Space Station Phase B request for proposals states that user equipment must behave as follows during three successive failures; fail operational (and safe), fail safe, and fail restorable (repairable).

7.5 SPACE LABS

The permissible failure level for all Spacelab batteries is Fail Safe/Fail Safe. That is, neither one failure nor two successive failures shall result in potential for harm to personnel or equipment.

7.6 SPECIAL INSTANCE OF LITHIUM BATTERIES

Lithium-based batteries are required to be two-failure tolerant, unless a more stringent requirement results from the sections above. That is, failure of two hazard controls on a lithium cell or battery shall not result in any hazard whatsoever to crew or other equipment. Note that tolerance of lithium cells to certain types of abuse may not be counted as a hazard control. However, failure of a cell may be counted as one of the failures.

An example of the above is as follows. A Li-BXC D-cell is being protected against venting hazard due to being overdischarged. The control is shunt diodes. For whatever reason, one cell in a series string runs out of capacity half-way through its rated capacity. This is one failure. A single shunt diode used as a hazard control fails short. This is a second failure. The fact that Li-BCX cells have demonstrated tolerance to overdischarge under these circumstances may not be cited as a second hazard control; a redundant shunt diode must be used instead.

8.0 GENERAL BATTERY SAFETY PRACTISES

The fact is often neglected that flight batteries are handled more on the ground than in flight. Ground personnel are involved in preparation of batteries for flight, installation into the Shuttle and whatever subsequent onboard prelaunch maintenance may be required.

The JSC Safety Manual (JSC-1700D), Section 5.4, gives a very good set of requirements for safe battery practises on the ground. This section is reproduced herein as Appendix F. Flight battery preparation, installation, and maintenance procedures should include all applicable provisions of this document for safety of ground personnel who handle batteries, either by quotation or reference.

APPENDIXES

APPENDIX A

GASSING CHARACTERISTICS OF SILVER-ZINC BATTERIES

The silver oxide-zinc alkaline battery, in normal operation and with sound intra-electrode dielectric insulation, will evolve only two gases, hydrogen and oxygen.

Oxygen is evolved only during charge and then only when an individual cell charge voltage exceeds the decomposition potential for water in the particular electrolyte (approximately 2 volts).

Hydrogen is evolved during open circuit stand, during discharge and when the gassing voltage is exceeded during charge. The amount of hydrogen evolved on stand is higher after a charge and decreases to an equilibrium rate which is logarithmically proportional to battery temperature and directly proportional to the quantity of zinc in the cell. The source of the hydrogen is the reaction of the electrolyte with the zinc negatives according to equation (1).

$$(1)\quad 2KOH + Zn \longrightarrow K_2ZnO_2 + H_2\ (gas)$$

During discharge, the amount of hydrogen evolved is reduced due to increasing non-availability of elemental zinc at the electrode-electrolyte interface. This is because the zinc is oxidized to zinc oxides and hydroxides by the discharge. The reaction of the electrolyte with oxidized zinc discharge products does not produce gas. See equations (2) and (3).

$$(2)\quad ZnO + 2KOH \longrightarrow K_2ZnO_2 + H_2O$$

$$(3)\quad Zn(OH)_2 + 2KOH \longrightarrow K_2ZnO_2 + 2H_2O$$

If a battery is heated during discharge, either by internal resistance losses or from an external source, there are two effects; (1) the rate of hydrogen evolution is increased due to the temperature dependence of the hydrogen evolving reaction and (2) occluded bubbles of hydrogen within the plates and separators increase in volume and escape from the cell. Thus, the amount of hydrogen generated from the cell will temporarily exceed the equilibrium values for the applicable instantaneous temperatures.

A silver-zinc battery cell which has a severe internal short circuit can evolve oxygen, hydrogen, and caustic vapor and the oxidation products of the organic materials in the separators and plastic cell containers. The rate and volume of each evolved material depends on the severity of the short circuit (amount of heat evolved), state of charge and amount of material available to vaporize, oxidize and/or decompose thermally.

Mixtures of hydrogen and oxygen are combustible in the composition range 4 percent to 94 percent hydrogen at STP (25°C, 1 atm.). In the composition range 18 percent to 94 percent, the combustion rate attains the explosive level, reaching a maximum explosive force when hydrogen and oxygen concentrations are at approximately their stoichiometric values (67 percent hydrogen and 33 percent oxygen). The energy required to catalyze the combustion is infinitesimal, on the order of 1 or 2 microjoules. A static or electric spark is sufficient to ignite a combustible mixture. This amount of energy is considered always present by people working with hydrogen (submarine battery personnel, for example).

Appendix A

APPENDIX B

hazardous conditions is not available. When implemented, these functions shall be capable of being tested for proper operations during both ground and flight phases.

205 CONTINGENCY RETURN OF PAYLOADS. Deployable payloads must provide the capability at all times prior to separation to safe the payload for contingency return. This safing includes performing contingency operations to reconfigure the payload to a safe condition for landing, and maintaining or resafing inhibits of hazardous functions to meet requirements of paragraph 202.

206 FAILURE PROPAGATION. The design shall preclude propagation of failures from the payload to the environment outside the payload.

207 REDUNDANCY SEPARATION. Safety-critical redundant subsystems shall be arranged so that the probability of propagation of failure of one to the other is minimized.

208 STRUCTURAL.

1. Structural Design. The structural design shall provide ultimate factors of safety equal to or greater than 1.40 for all STS mission phases except emergency landing. When failure of structure can result in a catastrophic event, design shall be based on fracture control procedures to prevent structural failure because of the initiation or propagation of flaws or crack-like defects during fabrication testing and service life.

2. Emergency Landing Loads. The structural design shall comply with the ultimate design load factors for emergency landing loads that are specified in JSC 07700, Volume XIV, attachment I.

3. Stress Corrosion. The selection of materials used in the design of payload structures, support bracketry, and mounting hardware shall comply with the stress corrosion requirements of MSFC-SPEC-522. For those applications in which MSFC-SPEC-522 requires the submittal of a materials usage agreement, the data shall be submitted as a waiver request in accordance with JSC 13830.

4. Pressure Vessels. Pressure vessels shall meet the ASME Boiler and Pressure Vessel Code, Section VIII, Divisions 1 and 2, or MIL-STD-1522. Where weight limitations prohibit meeting the above standards for flight vessels, NSS/HP 1740.1 shall be used as the standard with an ultimate safety factor of 1.5 or greater. Pressure vessels using MIL-STD-1522 or NSS/HP 1740.1 shall also be qualification tested to demonstrate no failure at the design burst pressure level. Pressure vessels using the ASME Code or MIL-STD-1522 shall also be qualification tested to demonstrate a life cycle capability of at least twice the maximum predicted number of operating cycles. Particular attention shall be given to insure compatibility of fluids used in cleaning, test, and operation with pressure vessels.

5. Pressurized Lines and Fittings. Pressurized lines and fittings with less than a 1.5-inch inside diameter shall have an ultimate factor of

safety equal to or greater than 4.0. Those with a 1.5-inch or greater inside diameter shall have an ultimate factor of safety equal to or greater than 1.5. Other pressure system components not considered pressure vessels, lines, and/or fittings shall have an ultimate factor of safety equal to or greater than 2.5.

6. Decompression. Payloads located within manned pressurized volumes designed to withstand decompression or subsequent repressurization shall be capable of tolerating the differential pressure without resulting in a hazard.

7. Sealed Containers. Sealed containers shall be analyzed to establish hazard potential. Containers with hazardous potential must be proof tested to 1.5 times the nominal pressure differential.

209 MATERIALS. Materials test data for hazardous fluid compatibility, flammability, and offgassing are contained in JSC 02681. JSC 09604 contains a listing of materials (both metals and nonmetals) with a "rating" indicating acceptability for each material's characteristics. The payload material requirements for hazardous materials, flammability, and offgassing are as follows:

1. HAZARDOUS MATERIALS.

   a. General. Hazardous materials shall not be released or ejected in or near the Orbiter. Hazardous fluid systems must contain the fluids after exposure to all STS environments unless the use of the Orbiter vent/dump provisions have been negotiated with the STS operator. Particular attention should be given to materials used in systems containing hazardous fluids. These include gaseous oxygen, liquid oxygen, propellants, oxidizers, and other fluids that could theoretically cause an exothermic reaction. Those materials within the system exposed to oxygen (liquid and gaseous), both directly and by a single failure, must meet the requirements of NHB 8060.1 for type D materials at the maximum use temperature and pressure. Materials within the system exposed to other hazardous fluids, both directly and by a single failure, must pass the fluid compatibility requirements of NHB 8060.1 for type J materials at maximum use pressure and temperature. The payload supplier's compatibility data on hazardous fluids may be used to accept materials in this category if approved by NASA.

   b. Mercury. The use of mercury or its compounds shall be minimized. Where used, the following information shall be documented prior to NASA approval:

      1) A list of equipment containing mercury to be used with justification for each use.

      2) The amount of mercury contained in the equipment.

      3) How the equipment is protected to prevent release of the mercury.

APPENDIX C

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MEMORANDUM

Lyndon B. Johnson Space Center NASA

REFER TO: EP5-84-M107	DATE JUN 2 0 1984	INITIATOR EP5/BJBragg:cmb:6/13/84:4701	ENCL 1

TO: Distribution

CC EP5/J. B. Trout

FROM: EP5/Chief, Power Branch

SIGNATURE William A. Chandler

SUBJ: Lithium Batteries in Back-up Power Applications

Small lithium batteries and button cells are used as back-up sources for micro- and milliwatt circuits such as clocks, CMOS, counters, RAMs, etc. A typical circuit is shown in figure 1. A high value resistor (100's of kilohms) may also be included at position A and a fuse may be included at position B.

A safety problem can exist in these various circuits if the blocking diode fails short-circuited and resistor A and fuse B have inadequate ratings to prevent significant charging currents to flow into the lithium battery from the parallel power supply. Tests at JSC have shown that such charging currents can cause certain types of lithium cells to explode violently. Not all of the wide variety of lithium-based cells have been tested and only limited quantities of any particular type have been tested. Hence, for equipment to be flown in manned space vehicles, certain circuit modifications have been necessary to insure safe operation. These modifications are in lieu of lengthy, expensive testing to determine the hazardous nature of any and all types of lithium cells.

In order to assess the safety of a particular battery circuit without extensive tests of the many batteries necessary to disclose a low rate of failure, the following data are necessary:

a. The current which the cell will pass in the charging direction when the lowest power supply voltage to reach the cell is applied. This would be the low end of the power supply output voltage tolerance, minus any impedances between the power supply and the cell (diode assumed shorted). The charge current should be determined using a sample of a five or more cells from each of two or more manufacturing lots, to evaluate variability.

b. Nominal current supplied to the load by the cell at its operating voltage with power supply off.

c. Minimum voltage to operate load.

With these data, a decision can be made concerning adding a fuse at B. Any fuse has a blow-time which is virtually instantaneous at some value of current larger than its rating. For example, Littelfuse picofuses blow within 5 seconds of applying a current equal to 200 percent of the fuse rating. Thus, determine a picofuse rating equal to half, or less, of the cell charging current determined above. If this rating exceeds the nominal load current supplied by the battery, it is a satisfactory fuse to insert at B in the battery circuit of figure 1, and the battery will be considered safe even if the diode fails short. However, when the fuse blows, there is no longer a back-up power source available.

If the fuse rating determined as above is less than the nominal load current supplied by the battery, such a fuse clearly cannot be used. In such a case, series redundant diodes must be used. Two series diodes are required for Fail Safe (FS) operation; three series diodes are required for Fail Safe/Fail Safe (FS/FS) operation. The additional diode(s) will reduce the voltage available from the battery circuit. Hence, it is necessary to evaluate the resulting voltage available versus the minimum voltage required to operate the load. If insufficient voltage is available, it will be necessary to add a cell in series with the existing cell. This, in turn, introduces the possibility of overdischarge of one of the series cells, which has been shown to result in violent venting of some types of lithium cells. Therefore, use of more than one cell in series will result in a further requirement to install an appropriately rated, protective shunt diode on each cell. One diode/cell is sufficient for FS operation; two parallel diodes/cell are necessary for FS/FS operation. Such arrangements are shown in figure 2.

Note that use of a current-limiting resistor at position A of figure 1 in lieu of shunt diodes where more than one cell is used, or in lieu of a fuse at position B where a fuse can be used, requires a determination of the minimum value of cell charging current below which no hazard can occur due to charging. Such a determination requires lengthy testing of a large number of sample cells if a low failure rate exists. Therefore, use of a limiting resistor is not recommended. Note also that means must be provided to check out the redundant diodes to verify continuing redundancy.

To summarize, the following hazard controls are necessary. They are shown in order of simplicity and assume avoidance of lengthy battery tests:

a. A blocking diode in the battery circuit is mandatory.

b. A fuse rated as determined above must be added if the relationship between fuse rating and load current permits it.

c. If a fuse cannot be used due to incorrect relationship between the fuse rating and the load current, series redundant diodes must be used.

d. If use of series redundant diodes requires compensation of voltage drop by an additional cell(s), shunt diodes must be used on the cells.

From all of the foregoing, it should be clear that it is simpler to use less energetic types of cells requiring less or no hazard controls in this application. Button cells or small cylindrical cells are available, made with silver-zinc, zinc-manganese alkaline, zinc-air, or even zinc-mercuric oxide couples, which can provide the required service, usually in nearly the same volume. The Power Branch (EP5) can assist in selection of appropriate cells.

This memorandum does not affect the status of equipment using back-up lithium cells which have already been certified for flight.

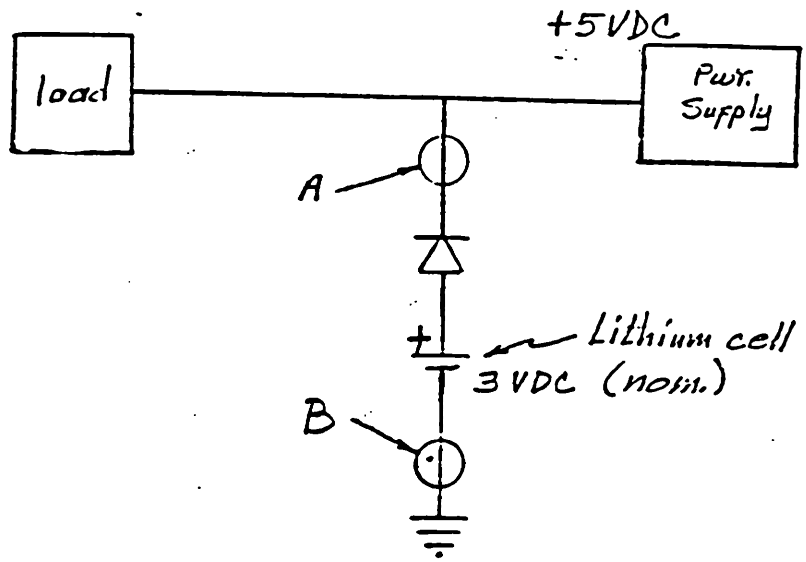

FIGURE 1

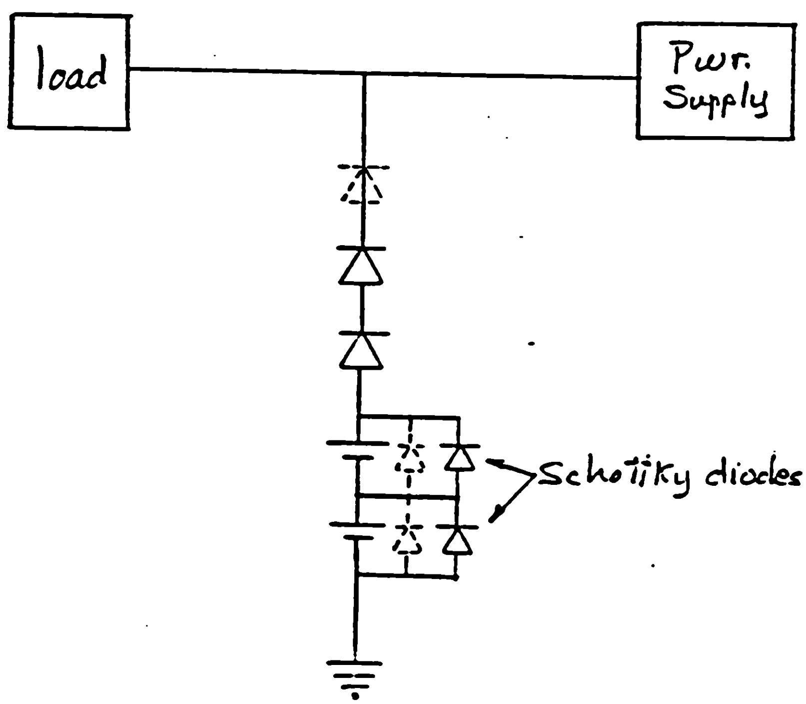

FIGURE 2

APPENDIX D

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NASA - Manned Spacecraft Center

MSC DESIGN AND PROCEDURAL STANDARD

STANDARD NO.	PAGE
116	1 of 2
EFFECTIVE DATE Nov. 3, 1967 (PS-41)	
REVISION DATE 3-6-70 (NO. 116)	REVISION DATE
REVISION DATE	REVISION DATE
REVISION DATE	REVISION DATE

TITLE

Mercury - Restriction on Use

STATEMENT OF STANDARD

The use of equipment containing mercury in liquid or vapor form (such as manometers, lights, thermometers, etc.) shall be avoided where the mercury could come in contact with the spacecraft or spaceflight equipment. Where the use of equipment containing mercury cannot be avoided, the following information shall be documented before using the equipment.

1. Prepare a list of equipment containing mercury to be used with justification for each use.
2. Determine the amount of mercury contained in the equipment.
3. Determine the protection necessary to prevent the release of mercury.
4. Develop a plan for decontamination in the event the mercury is released.

REMARKS

Mercury is a particularly hazardous liquid because of its toxicity and tendency to penetrate joints and amalgamate structural materials. Corona discharge can occur at low potentials in the presence of mercury vapor.

The intent of this standard is to prevent mercury, in any form, from coming in contact with any part of the spacecraft structure or equipment.

The application of this standard should require positive action or planning early enough in the program to evaluate alternate equipment or other test methods that do not use mercury.

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(See Page 2.)

Mercury must not be removed from metal surfaces with any abrasive cleaning method. The removal of oxide films on the metal will cause immediate mercury penetration.

Metal contaminated while under high stress will receive greater penetration of mercury and degradation of ability to withstand stress than metals under relatively low stress.

Mercury vapor in concentration of 0.01 milligram per cubic meter (or greater) is not acceptable for continuous occupancy. Equipment used to detect mercury in the crew compartment must be able to measure concentrations below this level.

REFERENCES:

1. MSC Design and Procedural Standard No. 33, "Toxicity - Materials Used in Habitable Areas."
2. MSC Design and Procedural Standard No. 41, "Shatterable Materials - Exclusion from Crew Compartment."

APPENDIX E

2.0 STS PAYLOAD HAZARDS DEFINITION.

2.1 PAYLOAD HAZARDS.- A hazard is the presence of any potential risk situation caused by an unsafe act or condition. There are numerous potential risk situations associated with the STS payloads which directly or indirectly affect the safety of STS flight or ground personnel. One of the purposes of this handbook is to assist the payload developer in recognizing the hazards associated with STS payloads. The identification of such hazards is the necessary starting point for the development of safety guidelines which may be used to eliminate or control the hazards.

Although there may be many secondary or contributory hazards, 10 basic hazard groups were identified as the primary concerns applicable to STS payloads. These hazards have safety implications during all mission phases on ground and flight crews, the STS vehicle, or other payloads.

The hazard groups were derived from a variety of sources such as: (a) a general knowledge of STS payload energy sources which are primary sources of hazards, (b) utilization of experience gained from previous manned space programs as to hazards encountered or prevented, and (c) other representative sources of hazard grouping or categorizations. The list of hazard groups used in this handbook is in general agreement with all such sources. A difficulty common to all lists, including this one, is that there is considerable overlap between hazard groups, and the assignment of any secondary hazard to a particular group can often be arbitrary. The manner in which hazards are grouped or subdivided is therefore not particularly significant. What is important is that the payload developer be aware of all the basic hazards associated with his payload.

2.1.1 Hazard Description.- The basic hazard groups, including representative examples of their causes and effects, are discussed briefly in the following paragraphs. The groups are numbered consecutively from 1 to 10 to agree with the hazard references in each subsystem guidelines index.

1. COLLISION.- This group involves those hazards which occur when payloads or payload elements are allowed to break loose and impact STS structure, other payloads, or flight and ground personnel. These hazards are caused by structural failure, procedural error or inadequate ground handling equipment. Failure of payload attach points can create equipment projectiles that can penetrate manned compartments and injure the crew. Penetration of the cabin may result in loss of cabin pressure and crew asphyxiation. Inadequate or incorrect procedures during payload deployment, retrieval, or during EVA (extravehicular activity) can lead to collision of the payload with the orbiter or other STS elements. Damage to critical orbiter control surfaces or primary structure is possible and could prevent a successful return to Earth. Ground handling equipment such as slings, cradles, holddown arms, etc., can fail and injure personnel during ground operations.

2. CONTAMINATION.- This group of hazards is associated with the release of toxic, flammable, corrosive, condensible, or particulate matter. Contamination is caused by leakage, spillage, outgassing, loose objects, abrasion, and from the growth of fungus or release of volatile condensible materials. Leakage of hazardous fluids or gases can be initiated from cracked or worn seals, gaskets, valve seats, flanges and joints. Spillage of liquids from containers, tanks or valves can directly, or indirectly by vaporization, degrade the atmosphere or equipment operation. Many materials outgas toxic products, irritants, or foul odors which can damage the senses, and the respiratory system of crewmen. Loose objects, dirt, and abrasive action within payload components can provide a source of particles that float in the zerogravity environment of habitable areas and can enter into the eyes, ears, noses, or mouths of personnel and into sensitive equipment. Fungi growing from materials providing nutrients in moist, warm environments are bacterial infection sources and contaminants in operating equipment.

3. CORROSION.- This group involves those hazards resulting from the structural degradation of metallic and nonmetallic equipment. Material corrosion can be caused by a variety of means. Leakage of corrosive or reactive material onto metallic or nonmetallic equipment can quickly degrade its usefulness. Material incompatibility or the joining of certain dissimilar metals can lead to corrosion. Environmental extremes of temperature and humidity are sources of deterioration of metals containing carbon or for most organic materials. Examples of the types of corrosive processes which can degrade metal and nonmetal equipment include stress corrosion, electrolytic corrosion, and polymerization. Causative agents will include acids, salts, solvents, halogens, etc. The effect of corrosion on equipment can lead to mechanical failures, premature wear, seizure, and short circuits. The loss of a critical function due to corrosion could lead to any of the 10 basic hazard groups identified herein, and the loss of crew, vehicle, or mission is possible.

4. ELECTRICAL SHOCK.- This group includes those hazards responsible for personnel injury or fatality because of electrical current passing through any portion of the body. Electrical shock can be caused by contact with a "live" circuit because of human error in performing an operation, a procedural error, or an equipment failure such as an insulation breakdown in exposed wiring. Other causes may be static electricity discharge, lightning strikes, or short circuits caused by moisture, bent connector pins, or wires, etc. Static electricity or lightning could be hazardous without adequate grounding or shielding protection. The effect of electrical shock can vary from a mild burn to loss of consciousness and electrocution. Cuts and bruises are possible from the involuntary reaction to the shock.

Other electrical system hazards affect the performance and operation of equipment and thereby affect the crew indirectly. Almost all payload subsystems are either electrically controlled or contain electrical components which can malfunction and cause almost any conceivable hazardous situation depending on the time and location of occurrence. For example, electrical arcing could result in fire or a faulty electrical circuit relay could cause premature activation of a pyrotechnic device. Electrical equipment malfunctions should therefore be considered as contributing factors for each of the 10 basic hazard groups.

5. EXPLOSION.- These hazards result from the the violent release of energy as a result of payload element overpressurization, fire, chemical reaction, excessive temperature, malfunctioning equipment or structural failure causing the release and collision of equipment with other structures or equipment. The overpressurization of pressure vessels, accumulators, batteries, etc., can result in explosion. Excessive temperature from a fire or a failed cooling system can result in explosion of cryogenic tanks, gas generators, pyrotechnic charges, squibs, etc. Equipment which can disintegrate explosively include pumps, motors, blowers, rocket motors, generators, lasers, etc. The effects of these explosive hazards on the crew could range from fragmentation injuries to eye or respiratory system irritation, burns, and asphyxiation. These effects would be the result of shrapnel or toxic/corrosive fluids or gases being released from the exploding component.

6. FIRE.- This group deals with the rapid oxidation of payload element combustibles. Fire can occur when a fuel and an oxidizer are exposed to an ignition source. It can also occur when hypergolics are inadvertently mixed. Fuels or combustibles consist generally of organic material, chemicals, and certain metals. Examples of these materials include rubber, wood, clothing, paint, plastics, solvents, and magnesium. Any high temperature device or source of electrical arcing or sparking can provide the ignition source for fire. Examples of these devices are bearings, motors, generators, heaters, lasers and faulty electrical wiring. The effects of fire can be catastrophic in the closed environment of a space vehicle. Death by asphyxiation, smoke inhalation, or burns are directly attributable to fire. The destruction of critical controls or life support equipment by fire can indirectly cause the loss of crewmen or the vehicle.

7. INJURY AND ILLNESS.- This group includes those hazards capable of inflicting physical injuries or illness of any sort on the flight or ground crews during all mission phases. Physical injuries may be caused by impact or collision with stationary objects having sharp edges or protruding parts or with shrapnel or projectiles from exploded tanks or accelerated loose objects. Physical injuries may also be caused by ingesting particulate matter, touching hot or cold surfaces, and by the loss of breathable atmosphere. Crew illness could result from exposure to pathogenic bacteria, toxic materials, or to excessive radiation levels.

8. LOSS OF ORBITER ENTRY CAPABILITY.- This group involves those hazards which could degrade the structural, aerodynamic, and thermodynamic integrity of the orbiter and could prevent its safe return from orbit. Such orbiter functional degradation can be caused by payload elements which cannot be retracted within the orbiter mold line or which prevent the closure of the payload bay doors. It can also be caused by payload element contact or collision with orbiter structural members, control surfaces, or primary insulation areas during payload deploy/retrieval activities. The payload elements preventing payload bay door closure include booms, antennas, solar panels, and other hinged or extendable/retractable components. Failure of such equipment may be caused by loss of electrical or hydraulic power, structural fracture, and jammed or malfunctioning retract mechanisms. Pressure vessel rupture, inadvertent firing of pyrotechnics or activation of propulsion systems could result in collision with sensitive areas of the orbiter. The eventual consequence of these hazards could be abandonment of the orbiter in space or possible loss of the crew and vehicle during an attempted entry.

9. RADIATION.- This group involves those hazards associated with the exposure of the human body and sensitive control equipment to ionizing radiation, ultraviolet or infrared light, lasers, and electromagnetic or RF (radio frequency) generating equipment. Ionizing radiation hazards may be caused by leaking or inadequately shielded radioactive equipment such as RTG's (radioisotope thermoelectric generators), particle accelerators, vidicons, liquid metal heat exchangers, etc. Overexposure of personnel to such radiation could result in tissue damage, permanent injury, or death. The crew could experience painful burns and eye damage from overexposure to ultraviolet or infrared light sources or to concentrated laser light beams. RF and electromagnetic radiation sources such as radar equipment and antennas can trigger ordnance devices or interfere with operation of critical communication equipment.

10. TEMPERATURE EXTREMES.- This group includes those hazards associated with the departure of temperature from normal. It also includes extreme heat or cold such as that generated by fire, cryogenics, and the environment of space. These hazards may be caused by insulation breakdown, short circuits, seal leaks, plumbing failures, and procedural and human error in handling or operating hot and cold generating equipment. Examples of equipment affected by temperature extremes include bearings, motors, electrical components, heaters, batteries, tanks, and lines. In addition to fire, these hazards can lead to structural degradation and mechanical equipment seizure. The ground and flight crews could suffer skin burns or frostbite as a direct result of contacting hot or cold materials. They could also be exposed to contamination hazards if overexpansion or retraction of payload components leads to the release of toxic matter.

APPENDIX F

5.4 BATTERIES

1. GENERAL

   This section identifies and provides control procedures for hazards inherent in battery handling, use, and maintenance. It also includes the procedure for developmental battery procurement and testing.

2. DEFINITIONS

   a. Cell. Basic unit for conversion of chemical energy to electrical energy and also for the reverse for rechargeable cells.

   b. Battery. One or more cells in a single package to provide DC power source.

   c. Primary. Cell or battery which is not to be recharged.

   d. Secondary. Cell or battery which is rechargeable.

3. GENERAL HAZARDS AND PRECAUTIONS

Batteries have the generic hazards of toxicity and explosion. They are a source of strong chemical solutions, either acid or alkali. Some batteries generate hydrogen during charging and discharging which, when mixed with air, is explosive. Some types of batteries are temperature sensitive and can vent and/or explode when the temperature is elevated either by external heat inputs or exothermic heat generated during battery discharge. Following are precautions to be taken in battery use and handling.

a. Metallic objects which could cause short circuits or arcing shall be kept away from battery terminals.

b. Rings, metal watchbands, chains, or other jewelry shall not be worn while handling or working on batteries. If a ring cannot be physically removed, it shall be covered with insulation, tape, or a glove.

c. When racks are used for support of batteries, they shall be made of materials nonconducive to spark generation or shall be coated to achieve nonconductivity.

d. A conveyor, an overhead hoist, or equivalent material handling equipment shall be provided for handling heavy batteries such as those used in industrial trucks and materials handling equipment.

e. When using overhead lifting devices, a suitable spreader shall be used to prevent the lifting cables or chains from exerting compressive forces on the sides of the battery.

f. Battery terminals and exposed conductive surfaces shall be protected with nonconductive materials when cables or chains are used for lifting.

g. Suitably designed terminal straps shall be used for lifting batteries, unless the battery case is designed with suitable lifting pad eyes or similar attachment points.

h. When manual lifting is necessary, sufficient help should be provided to prevent injury to personnel.

i. Special precautions are required when servicing and charging storage batteries since at such times the workers will be exposed to acids, alkalines, and hydrogen gas.

j. Battery rooms shall be equipped with mats and/or wooden slat floors to prevent slips or falls and to protect personnel from shock.

k. Adequate ventilation systems shall be provided.

Page II-5-7 not applicable

l. The cases of switches, controls, lights, and indicators shall be grounded in accordance with the National Electrical Code.

m. AC and DC circuits shall be routed separately (except in technical systems).

n. Charging equipment shall be equipped with a status display to indicate conditions of system; e.g., charging, discharging, on, off, etc.

o. Battery shops shall be equipped with an eyewash fountain.

p. The battery rack or cabinet shall be equipped with a disconnect device.

q. The use of unvented lead-acid and nickel-cadmium batteries is prohibited, except as provided in paragraph 5.4.5(c).

r. Explosion proof vent caps shall be used.

4. RESPONSIBILITIES

All JSC organizations and their contractors who plan to purchase, design, develop, or build a device that incorporates an electric battery must coordinate and obtain approval from the Operations Safety Branch and the Power Branch. The exceptions to this requirement are listed in the following paragraph as exempt applications. Procedures for the procurement, storage, testing, handling, maintenance, and use of all batteries are subject to approval by the Center Operations Directorate and the Power Branch. The Power Branch will prepare users' manuals for new types of batteries as they are tested and approved for use.

5. EXEMPT BATTERY APPLICATIONS

Lead-acid, nickel-cadmium, or nickel-iron secondary (storage) batteries used in the following applications need not be approved before use at JSC.

a. Starting, lighting, ignition, or motive power in:

(1) Vehicles such as cars, trucks, buses, mobile cranes, mobile man-lifts, electric drive wheelchairs, earth moving equipment, forklifts, and other materials handling equipment.

(2) Standard boats and aircraft.

b. Facility emergency lighting systems, emergency communications systems, or other commercially available emergency power systems.

c. Leclanche, mercuric oxide-zinc, alkaline-manganese, and silver-zinc primary, cylindrical and button-type lead-acid, nickel-cadmium, and silver-zinc secondary and lead-acid batteries having immobilized (gel-type) electrolyte used in the following nonflight, commercially purchased, personal equipment:

(1) Calculators and small computers

(2) Watches and clocks

(3) Radios and walkie-talkies

(4) Flashlights and lanterns

(5) Cameras

(6) Portable sound and video recorders and players including battery-operated microphones and television sets.

(7) Hearing aids

(8) Radiation detectors (Radiacs)

(9) Metal detectors

(10) Test equipment (e.g., multimeters, ohm-meters, pyrometers)

d. The major bases for exemption are as follows:

(1) The battery uses an electrochemical couple which is well known, well understood, and which has a long application history. The various types of lithium batteries, for example, are not exempt regardless of type, size, application, or assumed degree of harmlessness.

(2) The application itself is of a commonly used, commercial design, is generally available commercially, usually is accompanied by a user's manual that describes use and/or maintenance of the battery, and uses a battery for which the hazards (if any) are well known and are controlled by specific features of the application's design.

(3) The application is nonflight.

6. DEVIATIONS

Users having a battery application not specifically listed in paragraph 5.4.5 above shall coordinate their requirements and battery application with the Operations Safety Branch and the Power Branch. Center users may request a deviation from these requirements in accordance with the procedures specified in paragraph 5.4.4 preceding.

7. LEAD-ACID BATTERIES

a. Basic Requirements

(1) A face shield or goggles shall be worn when handling or servicing a battery.

(2) Servicing and charging installations shall be located in areas designated for that purpose.

(3) Batteries for emergency or alarm systems shall be protected with substantial guards or barriers or be so located as to preclude damage from external sources.

(4) Charging equipment for industrial trucks shall be guarded to prevent damage by the trucks.

(5) Replacement batteries for industrial trucks shall be of the same weight as the orginal batteries or of a heavier weight. The use of lighter weight batteries shall be prohibited.

(6) Industrial trucks or vehicles for in-place charging shall be properly positioned with brakes applied before attempting to change or charge batteries.

(7) Lead-acid batteries shall be turned in to the Technical Services Division, Space Battery Facility, Building 9, for disposal.

b. Explosion and Fire Hazards

(1) Ventilation shall be provided to ensure diffusion of hydrogen from batteries to prevent the accumulation of an explosive mixture. Mechanical ventilation may be required for certain applications.

(2) Smoking shall be prohibited in vicinities where batteries are being charged, serviced, or worked on; in battery rooms; and in the vicinity of battery cabinets. "No Smoking" signs will be posted.

(3) Precautions shall be taken to prevent open flames, sparks, or electrical arcs in the areas listed in paragraph 7b(2).

(4) Fire protection shall be provided in battery rooms and charging areas if combustible materials are present.

(5) When charging batteries in industrial trucks or other equipment containing battery compartments or battery covers, the compartment or cover shall be open to aid ventilation and heat dissipation.

(6) No work involving the use of a heat source or arcing device will be performed on batteries until positive venting of hydrogen and/or oxygen gases has been assured. This may be accomplished by purging with an inert gas or by positively ventilating all spaces in which explosive gas mixtures could be trapped.

(7) Stationary battery installations and all other feasible installations shall have each cell equipped with a flash arrester vent cap.

(8) A periodic inspection schedule shall be established that will ensure that the electrolyte level in the emergency light battery cells does not fall below the level of the plate tops.

c. <u>Chemical Hazard</u>

(1) Face shields or goggles, protective aprons, gloves, and boots shall be worn by workers while mixing electrolyte, activating dry charged batteries, or performing any work which could result in an electrolyte spill.

(2) A water source for quick drenching of the eyes and body shall be provided within 25 feet of the area in which the activities listed above are being performed in designated battery servicing and charging installations. <u>CAUTION</u>: In the event the electrolyte comes into contact with the skin or clothing, the affected portion should be flushed with copious amounts of water, and medical attention should be obtained immediately. If the electrolyte gets into the eyes, flush eyes thoroughly and continuously with <u>water only</u> for a minimum of 15 minutes, rolling the eyes, and lifting the eyelids for thorough removal of the electrolyte. <u>DO NOT</u> put a neutralizing solution in the eyes. Get medical attention immediately. The assistance of a second person may be required so that the flushing can be effectively performed.

(3) Any area in which operations involve the use of electrolyte other than that already in batteries shall be provided with facilities for flushing and neutralizing spilled electrolyte.

(4) Charging benches or tables shall be coated with a nonconductive material impervious to the electrolyte.

(5) Sufficient ventilation shall be provided to prevent acid fumes from entering areas in which alkali batteries are serviced or used.

(6) Precautions shall be taken to service alkali-electrolyte batteries in an area isolated from lead-acid batteries.

(7) Equipment used with the electrolyte when servicing or working on acid and alkaline electrolyte batteries shall be kept separate and carefully labeled. Do not interchange equipment. Use of acid electrolyte in an alkaline cell can cause large amounts of hydrogen to evolve.

(8) When batteries are charged, the vent caps should be kept in place to avoid electrolyte spray. Care shall be taken to assure that vent caps are functioning. If the vents are clogged, the battery case may rupture from internal overpressure causing electrolyte to spray over a large area.

(9) A carboy tilter or siphon shall be provided for handling electrolyte.

(10) When electrolyte is being mixed, acid shall be poured into water; <u>CAUTION: WATER SHALL NOT BE POURED INTO ACID</u>.

8. <u>NICKEL CADMIUM CELLS (HANDLING PROCEDURES)</u>.

a. When vented nickel cadmium cells or caustic electrolyte are handled, safety goggles, protective gloves, and a protective apron shall always be worn. Potassium hydroxide is a very caustic electrolyte that can cause severe burns; therefore, if electrolyte gets on the skin or in the eyes, flush with copious amounts of water for 15 minutes and then obtain medical assistance.

b. Always charge vented nickel cadmium cells in a well ventilated area according to manufacturer's recommendations.

c. Adjust the electrolyte in each cell in accordance with the manufacturer's procedures. Maintain the electrolyte level above the plate tops.

d. Select cells for each sealed cell battery for charge voltage and capacity match and charge retention.

e. Charge the battery in a well-ventilated area with the battery box cover completely removed. NOTE: Make sure individual cells are able to dissipate heat to prevent thermal runaway. Individual vented cells shall be equipped with flash arrestor vent caps.

f. To reduce gassing and subsequent electrolyte spewing, a voltage limited current taper charging method is recommended. Follow manufacturer's instructions carefully regarding charging methods.

g. Do not replace the battery box cover until the battery has been cleaned and at least 4 hours have elapsed since termination of charge.

h. Assemble the battery in a container separate from the rest of the electrical system.

i. Do not use porous materials for packing as they entrap gases or liquids.

j. In designing a portable battery container for vented cells:

(1) Reduce the void volume in the battery package to an absolute minimum.

(2) Coat the battery cell terminals, cell interconnects, and wiring with a suitable alkali-resistant potting material, or, preferably, pot the entire battery in a suitable material to encapsulate all wiring and terminals. NOTE: Make sure that vented cells are not sealed by potting material.

(3) Provide an easily removable cover for the battery container.

(4) Relieve the battery container with a splash-proof pressure vent. <u>Ensure that all individual cells are vented.</u> NOTE: Do not seal vented cells in a container that will trap gases.

k. Batteries other than lithium batteries shall be turned in to the Technical Services Division, Space Battery Facility, Building 9, for disposal.

9. <u>LITHIUM PRIMARY BATTERIES AND CELLS</u>

a. <u>General Requirements</u>

(1) The lithium cells are not designed to be serviced or charged. Inadvertent charging could cause the cell(s) to vent or explode.

(2) Highly toxic and corrosive materials are released by a vented or burning lithium cell. The materials vary with the kind of material used in the electrolyte and the positive active material. Some of the main toxic ingredients of the released materials are CO (carbon monoxide), HC_1 (hydrochloric acid), HBr (hydrobromic acid), CH_4 (methane), CH_3CN (methyl cyanide), SO_2 (sulfur dioxide), H_2 (hydrogen), HCN (hydrocyanic acid), $SOCl_2$ (thionyl chloride), and CS_2 (carbon disulfide). Thus, whatever the type of cell involved, if it vents or catches fire or is in a fire, proper precautions must be taken to avoid inhalation of or skin contact with the fumes.

(3) Because of the hazards involved in handling and using lithium cells, caution is mandatory. When abnormal use has been determined or if cells are observed to be leaking, venting, or increasing in temperature, the area should be cleared of personnel and the batteries should be removed to a safe area by qualified and properly equipped personnel. If possible, the cell(s) should be disconnected electrically from

associated equipment. After the cells have stabilized, they may be disposed of in accordance with instructions in paragraph 5.4.9a(4) below.

(4) Since all cells contain toxic materials and materials classified as hazardous by the EPA and, therefore, require collection, they must be transported to the Thermochemical Test Branch in such a manner that will prevent short circuiting, and turned in to TTA personnel for disposal in an authorized manner.

(5) The lithium cells should be stored indoors at room temperature or lower in a dedicated, dry, well ventilated location.

(6) Prior to handling lithium cells/batteries, personnel must be trained in their use.

b. Explosion and Fire Hazard

(1) Handling and safety procedures. In the event of a small fire, graphite powder or a Lith-X (class D) extinguisher should be used to extinguish burning lithium. Do not use water, sand, carbon tetrachloride, CO_2, or soda acid extinguishers on lithium cell fires. These types of extinguishing agents may be utilized on nearby materials to prevent the spread of the fire to other combustible material.

(2) Short-circuit and high-current discharge. Some lithium cells are capable of delivering high-current outputs. Under short-circuit and high-current discharge conditions, the cell(s) may overheat and then vent or explode.

(3) Overheating and incineration. Lithium cells are not to be exposed to elevated temperatures beyond those that tests and certification allow. Expended cells will be disposed of in accordance with paragraph 5.4.9a(4) and not incinerated.

(4) Over or forced discharge. Extended continuous discharge of a cell below zero voltage, or into voltage reversal, could cause the cell to vent or explode.

(5) Destruction. The lithium cells should not be opened, crushed, punctured, or otherwise mutilated as this will release toxic and corrosive materials. (Refer to previous paragraphs regarding disposal.)

c. Specific Lithium Primary Batteries and Cells

(1) Lithium-sulfur dioxide cells/batteries. Lithium sulfur dioxide batteries shall not be utilized unless specifically approved by the Power Branch and Operations Safety Branch. The Goddard Space Flight Center Handbook, GHB 1710.5, Lithium-

Sulfur Dioxide Cell and Battery Safety, dated June 12, 1981, shall be utilized as a guide after specific approval is granted. Copies of this document are on file in the Propulsion and Power Division and the Operations Safety Branch.

(2) Lithium bromine complex cells/batteries.

(a) Under normal conditions the hermetically sealed Li-BCX (lithium-bromine complex) cell has been approved for limited use. However, in the event of abuse, such as testing beyond the manufacturer's recommendations, deliberate or accidental shorting, cell reversal, exposure to high temperatures, or exposure to previously untested conditions, the cells have been known to vent toxic materials and/or explode.

(b) Overheating and incineration. The lithium-BCX cells can be safely operated at temperatures up to 160° F. Temperatures above 200° F could cause cells to bulge; and temperatures above 250° F could cause cells to vent or explode.

(3) Lithium CSC (chloride sulfural chloride) cells/batteries. CSC cells/batteries are not to be used.

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